REEFix: *Coral Protection Hydrogel*

PRESENT TECHNOLOGY

Today, various technologies are employed to target microplastic (MP) pollution and reduce coral degradation. While these technologies have demonstrated some success in MP removal and monitoring, they fail to address the root causes of MP-induced coral damage and do not actively promote coral recovery.

One common strategy is MP filtration, which aims to capture MPs before they reach marine ecosystems. In sand filtration, plastic particles adhere to sand grains, removing fine contaminants as water flows through layered filtration beds. Although effective for larger particles, this method struggles to capture MPs smaller than 20 μm and is prone to clogging. Additionally, shear forces within the filter bed can fragment larger MPs into smaller particles that exacerbate pollution (Puteri et al., 2025). Membrane filtration techniques utilize semi-permeable barriers that function through pores of specific diameters, physically blocking larger particles as well as electrostatic forces and hydrophobic interactions between MPs and membranes (Pinto et al., 2025). Despite their effectiveness, membrane filtration systems require significant chemical and energy inputs, along with frequent backwashing and physical cleaning, making this technique impractical for large-scale, long-term reef protection.

Recently, hydrogels have emerged as promising materials for mitigating MP pollution and MP-induced coral stress. Hydrogels are three-dimensional polymer networks capable of absorbing large volumes of water using hydrophilic functional groups that form hydrogen bonds and electrostatic interactions with surrounding water molecules (Bashir et al., 2020). Hydrophobic interactions, van der Waals forces, and electrostatic attraction between the hydrogel surface and plastic polymers enable the adsorption of organic pollutants. Their highly porous

structure, large surface area, and regions of varying polarity make them effective for MP removal in water systems (Mukherjee et al., 2025). Advances in hydrogel design have incorporated embedded photocatalysts, such as copper-substituted polyoxometalate (Cu-POM) nanoclusters, which utilize UV light to chemically degrade plastic polymers (Dutta et al., 2024). However, current hydrogels lack adaptive self-repair, so structural damage from environmental stressors compromises their protective and adsorptive functions. Additionally, these hydrogels focus solely on MP removal and do not restore existing coral tissue damage.

Our proposed REEFix hydrogel advances beyond existing technologies through a self-healing, nanotechnology-enhanced hydrogel designed for coral application. Unlike remote filtration systems, our gel will operate directly at coral surfaces, preventing MP-induced abrasion and degradation. Embedded nanoscale sensors will detect localized coral stress signals, enabling targeted deployment. The biodegradable design will reduce maintenance required, while vesicle-based delivery of restorative compounds actively supports coral surface healing, addressing pre-existing damage rather than merely preventing further exposure. Thus, our gel can simultaneously restore damaged corals and prevent additional MP-induced harm, and can be developed through emerging advances in self-healing hydrogels and nanoscale technologies.

HISTORY

The rise of the Industrial Revolution spurred the development of synthetic polymers in 1869. John Wesley Hyatt treated cellulose derived from cotton fiber with camphor to create plastic. Further discoveries led to the invention of Bakelite, the first fully synthetic plastic containing no naturally occurring molecules. As major chemical companies invested in plastic research and development, plastics became increasingly integrated into society. During the start

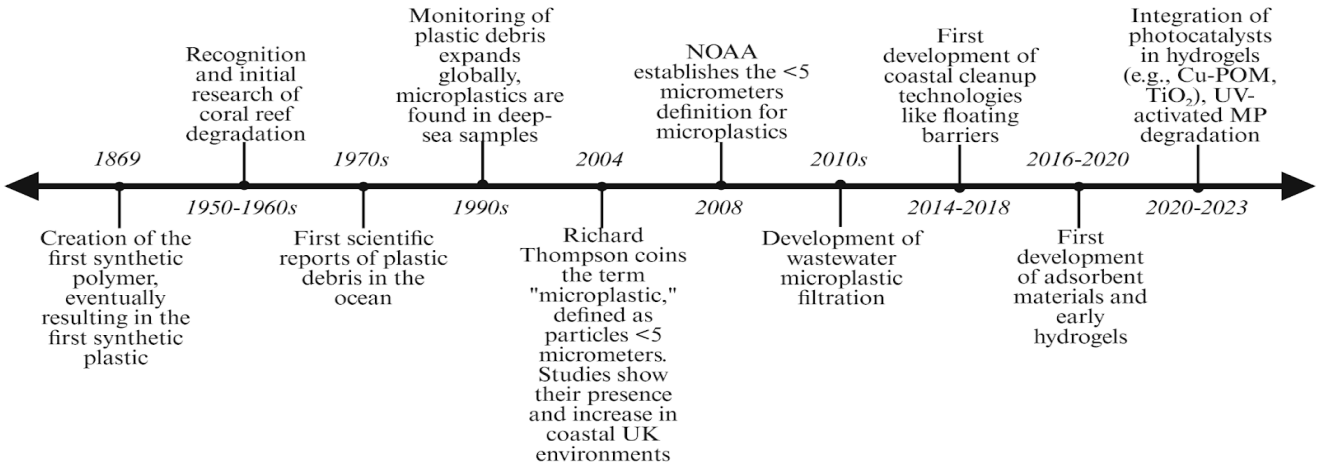

Figure 1. Timeline of synthetic polymers, coral reef degradation, microplastics, and restorative technologies that have emerged over time. *Figure created by student researchers, BioRender, 2026*

of World War II, plastic was widely adopted in nylon for parachutes and plexiglass for aircraft windows **(Figure 1)** (Science History Institute Museum & Library, n.d.).

As plastic production increased, environmental consequences became evident. In the late 1960s and 1970s, systematic monitoring of Caribbean reefs expanded in response to widespread decline in corals. Outbreaks of “white-band disease” were attributed to anthropogenic stressors such as pollution and ocean warming (Jackson et al., 2014). By the late 1980s, mortality rates of corals and sea urchins exceeded 90% (Cramer et al., 2020). Around the same time in 1972, the first scientific findings of marine plastic debris were published, reporting small plastic particles in the Sargasso Sea (Carpenter et al., 1972; Carpenter & Smith, 1972; Colton et al., 1974; Carpenter, 2022). In 1986, long-term monitoring of surface plastic debris revealed widespread, persistent plastic pollution (Law et al., 2010; Rochman, 2020). In the next decade, plastic debris was documented on deep-sea floors as well (Galil et al., 1995; Galgani et al., 1996).

The term “microplastics” was formally defined in 2004 (Thompson et al., 2004). Soon after, it was discovered that MPs facilitate the accumulation of toxic contaminants such as phenanthrene in marine organisms (Teuten et al., 2007). Subsequently, the National Oceanic and Atmospheric Administration (NOAA) held an international research workshop in 2008,

establishing the first size-based MP definition as particles 5 mm or smaller, enabling consistent measurement and comparison across ecological studies (Courtney et al., 2009; Ho et al., 2025).

By 2015, research shifted toward MP removal technologies, including filtration, membrane bioreactors, and magnetic separation systems (Talvitie et al., 2015). These innovations achieved 80-99.9% removal efficiency, demonstrating substantial progress in both the technology and effectiveness of microplastic mitigation (Talvitie et al., 2017; Bendix, 2019).

FUTURE TECHNOLOGY

Our technology design for the novel REEFix hydrogel involves self-healing, marine-grade hydrogels that actively repair damaged coral and protect against further MP-driven degradation **(Figure 2)**. Over the next decade, it is envisioned to evolve into a largely autonomous coral restoration system capable of long-term deployment with minimal human intervention. Coral recovery timelines will vary by species and environmental conditions, and specific recovery periods will be aligned with chemical cues corals produce. Unlike current passive MP pollution mitigation strategies, REEFix will function directly at the coral-environment interface, promoting coral recovery while protecting against further damage.

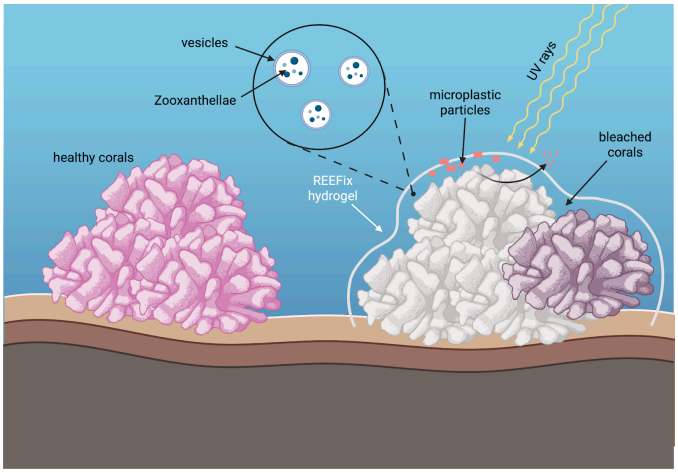

Figure 2. REEFix hydrogel design incorporates Cu-POM catalysts to degrade microplastics and vesicles containing zooxanthellae to revive bleached corals, instilling color back to the reefs. Figure created by Student Researchers, BioRender, 2026

REEFix will act as a physical and chemical barrier against plastic abrasion, UV radiation, and oxidative stress. Nanoscale agents embedded in the hydrogel would detect coral damage

through chemical cues such as elevated reactive oxygen species (ROS), pH shifts, or microfractures on the coral surface. These agents are designed to detect coral damage through integrated chemical and mechanical transduction pathways rather than relying on single signals. If damage is detected, the gel will then anchor to the porous ridges of the damaged coral skeleton and form a thin, adaptive coating that conforms to the coral topography without penetrating or damaging tissue. ROS sending is based on threshold-dependent redox chemistry. As the corals are naturally transient, low levels of ROS fluctuation are a part of normal metabolic signaling. Furthermore, the nanoscale agents will undergo irreversible bond cleavage, resulting in kinetic filtering, which would allow the system to distinguish pathological oxidative addresses from normal signaling events. pH sensing relies on confined measurements rather than large, insignificant values. The hydrogel contains pH-sensitive polymers whose protonation state only changes within a narrow pH window regarding coral stress. Temporal resolution in minutes to hours is sufficient to differentiate short-term environmental fluctuations.

To actively address MP pollution, Cu-POM catalysts will be incorporated into the hydrogel matrix. These catalysts will promote the photocatalytic degradation of MPs absorbed into the hydrogel using UV light. The hydrogel will contain stress-responsive polymer networks that aid in self-healing by reforming molecular cross-links following mechanical abrasion or chemical stress. This will preserve the hydrogel's coral-protecting functions for extended periods without requiring external maintenance or reapplication. Additionally, molecular vesicles containing Zooxanthellae will be embedded within the gel to support coral recovery with carbon dioxide, dissolved inorganic nitrogen, and phosphorus to support Zooxanthellae survival. Once the hydrogel anchors to the coral, nanoscale agents will trigger localized vesicle release, delivering the Zooxanthellae that provide essential nutrients for coral building.

The REEFix hydrogel will also be engineered using marine-safe materials to be biodegradable once long-term protection is no longer needed. Once coral recovery is completed and the nanoscale agents no longer detect coral damage, the hydrogel will break down into non-toxic components to prevent secondary pollution. This controlled degradation will allow healthy corals to continue interacting with the outside marine environment normally.

BREAKTHROUGHS

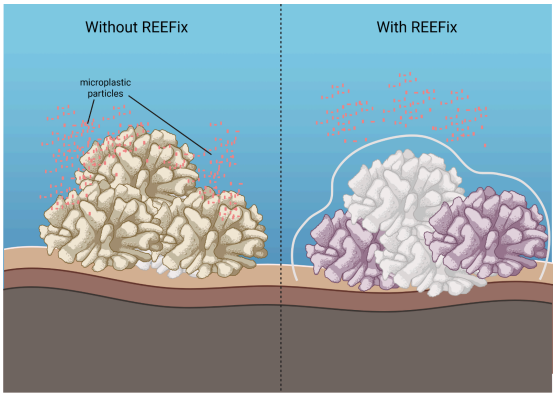

Figure 3. REEFix rehabilitation impact on bleached coral reefs. Figure created by Student Researchers, BioRender, 2026

Hydrogel technologies are already advanced; however, further breakthroughs are required to make the development of hydrogels that repair coral damage possible. A significant breakthrough for this technology would be the development of a self-healing hydrogel that functions reliably under mechanical stress in marine environments. The hydrogel must repeatedly restore its molecular structure after abrasion or deformation while remaining anchored to the coral surface. This would require advances in reversible cross-linking networks that can reform rapidly without weakening over time, which could utilize dynamic covalent bonds, hydrogen bonding networks, or metal-ligand coordination **(Figure 3)** (Yu et al., 2021).

Another critical breakthrough is the creation of marine-grade, biodegradable materials that break down into non-toxic compounds. This calls for advances in polymer design to ensure long-term compatibility and ecological safety. Furthermore, the REEFix technology depends on the development of highly sensitive nanoscale sensors capable of detecting coral stress in real time. Although sensors exist for measuring chemical changes such as ROS or pH fluctuations,

these sensors have primarily been used for biomedical applications, and integrating these sensors into a marine hydrogel remains difficult (Yuan et al., 2025; Ahmed et al., 2025).

Experimentation would be conducted to evaluate the REEFix hydrogel, which would utilize seawater tanks containing live coral fragments. The hydrogel would be applied to coral surfaces and would serve to protect against any mechanical damage and simulated wave and sediment stress. The study can then compare untreated coral, coral with standard hydrogels, and coral treated with the self-healing hydrogel over the span of one healing cycle. Control groups would include hydrogels without Cu-POM catalysts, hydrogels without vesicles, and hydrogels without self-healing networks to fully attribute the effects on coral health and reduction of MP pollution to REEFix. To assess hydrogel performance and coral health, changes in coral growth rates, brightness and saturation of coral color, ROS concentration, and pH near the coral surface would be measured, while controlled temperature, ranging from 23°C to 29°C, based on average optimal growth temperatures for species-specific coral growth, and UV exposure will remain constant. Additionally, microplastic accumulation and degradation rates would be quantified by utilizing radiolabeled or fluorescently-tagged microplastics.

DESIGN PROCESS

During the development of the REEFix technology, our team explored several alternative design ideas before finalizing our hydrogel-based system. Initially, we designed the hydrogel to fully coat entire coral colonies to create a continuous physical barrier against MPs, UV radiation, and abrasion. Although this physical barrier would serve to protect all coral surfaces from MPs, fully covering corals would eventually disrupt natural nutrient exchange, blocking feeding pathways for fish and other reef-associated organisms. Thus, we decided to incorporate nanoscale sensors to allow the hydrogel to attach only to damaged corals, similar to how a

Band-Aid covers a wound. We further included a degradation component to our hydrogel to allow for normal interactions between the coral and the environment after coral damage is healed. Another idea considered was embedding a filtration system within the hydrogel to physically capture and remove MP particles from the surrounding water. Although this method seemed promising, we determined that filtering mechanisms would be too easily clogged due to organic debris, sediment, and biofouling. Specifically, studies revealed that membrane flux would decline from the formation of biofouling on the membrane surface, increasing energy consumption due to higher pressure being required to overcome the resistance and flux decline (Nguyen et al., 2012; Abd El Aleem et al., 1998; Vrouwenvelder and van der Kooij, 2003). Furthermore, biofouling progression– particularly the attachment of microbes and diatoms, the settlement of invertebrate larvae and algae spores, and macrofouling assemblage development– within tropical waters would significantly reduce the efficiency of the system over time (Iswadi et al., 2022). Instead, we decided on embedding Cu-POM catalysts as a more sustainable and reliable solution for long-term reef protection. These catalysts actively degrade MP particles through photodegradation when exposed to UV light, allowing for continuous MP reduction without mechanical blockage.

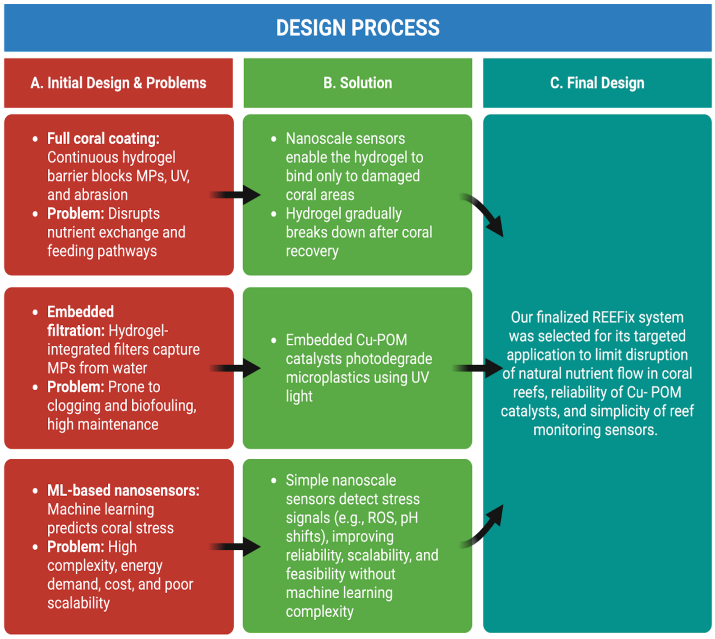

Figure 4. REEFix design process. *Figure created by student researchers.*

When developing REEFix, we also wanted to incorporate machine learning algorithms into the nanoscale sensors to predict coral stress (Chowdhury et al., 2024). While this feature would enhance hydrogel deployment precision, it would greatly increase system complexity, energy use, and cost due to the need for data pre-processing and algorithm training. As the tasks that the machines perform increase in complexity, they become more data-intensive, requiring more memory storage and energy. Estimates show that by 2030, the energy consumption of such machines is projected to rise between 8-21% of the global electricity supply (Magubane 2023). Thus, we opted for simpler nanoscale sensors that rely on chemical cues to detect physical coral damage. These sensors are simpler, more robust, and consume less power than machine learning-based detection systems, making them more feasible for continuous deployment in marine environments.

CONSEQUENCES

Introducing REEFix could yield significant environmental benefits for marine ecosystems, particularly through enhanced coral reef protection and recovery. By selectively protecting damaged corals, REEFix supports regrowth and resilience while minimizing interference with healthy reef areas. REEFix also delivers zooxanthellae, providing a primary nutrient source that combats coral stress and promotes coral building and repair. Studies have demonstrated that nutrient enrichment by zooxanthellae dramatically accelerates coral growth up to threefold, so we expect targeted delivery of zooxanthellae by REEFix to have similar effects (Al-Hammady et al., 2013). Another restorative benefit is the reduction of MP pollution in marine environments. Since REEFix utilizes Cu-POM catalysts, the hydrogel can actively degrade MPs into less harmful byproducts, reducing long-term accumulation in marine ecosystems (Dutta et al., 2024). Not only does this mitigate the stress MPs cause to coral reefs,

but it also limits the ingestion of MPs by marine organisms. Over time, this could contribute to improved ecosystem health and reduced biological stress on reef species. A further positive consequence includes long-term environmental safety. The biodegradable material that makes up the hydrogel breaks down into nontoxic byproducts after coral reef recovery is complete, which ensures that the technology does not leave harmful residues behind. Typical hydrogels developed specifically for marine environments are environmentally benign, as they are alternatives to toxic anti-fouling paint (Lin et al., 2022; Murosaki et al., 2012; Wang et al., 2024). This feature reduces ecological risk and supports sustainable reef management practices.

Although there are significant positive consequences to the implementation of REEFix, there are also some negative consequences that must be considered. When the technology attaches to corals, it could block feeding interactions between fish and corals or disrupt nutrient exchange. As an attempt to address this limitation, the hydrogel would selectively target only damaged coral tissue, allowing the sensors to identify coral stress and not attach to healthy corals. As a result, corals available for fish feeding would become limited, preventing fish from obtaining nutrients from the corals with the REEFix gel covering them, as it is not completely guaranteed that the nanotechnology within REEFix is completely accurate. Additionally, since the hydrogel is transparent and allows sunlight penetration, MPs in surrounding waters may undergo photodegradation outside of the hydrogel, which allows for the release of additives and degradation products into the marine environment. We considered incorporating a component within REEFix that acts as “sunscreen,” protecting the corals from further degradation of MPs and preventing them from penetrating the coral membranes. However, since the bleached corals require zooanthellae (microalgae) to reobtain their color, the “sunscreen” protecting the corals would not work, as it would prevent the corals from regaining their color and force them to

remain bleached and vulnerable to MP damage. In addition, common chemicals used in sunscreen products to filter or block harmful UV radiation have been found to negatively impact coral reefs, specifically oxybenzone and octinoxate (Hope, 2019).

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